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TANK STRATIFICATION WITH A FLEXIBLE MANIFOLD

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ABSTRACT

Use of a flexible, porous manifold to increase the level of storage tank stratification in domestic solar water heating systems is studied in a 372-liter storage tank. The initial tank temperature profile, inlet temperature, and test duration are varied in three testing schemes. Flow rate is 0.07 l/s. Stratification level is quantified by vertical temperature profiles and a new dimensionless mix number based on the energy in the storage tank weighted by vertical location. The mix number ranges from 0 to 1, with 0 representing a perfectly stratified tank and 1 representing a fully mixed tank. Results show that under operating conditions typical of direct, constant flow rate solar systems, an orlon manifold is 48 percent more effective than a conventional drop-tube at achieving stratification.

1. INTRODUCTION

Thermal stratification in solar storage tanks is a critical factor in the design of effective water heating systems. Methods of increasing stratification include: operating with flow rates low enough to turn over the tank only once a day ("single-pass"), isothermal operation, and/or use of a stratification enhancing distribution manifold. Manifolds have the advantage over the other options of providing tank stratification without requiring modifications in system operation.

Manifolds can be made of either rigid porous tubes or flexible porous fabrics (1-6). Design of these devices is based on matching the pressure gradients of the manifold fluid and the tank fluid to prevent inflow or outflow from the manifold until the fluid returning from the collector reaches the location in the tank where tank temperature equals return fluid temperature. Because rigid manifolds use vertical resistance elements to match pressures, they are difficult, if not impossible, to design to operate effectively over a range of temperatures and flow rates. Flexible manifolds adapt to different operating conditions because pressure gradients in the tank and the manifold are matched continuously by variations in the cross-sectional area of the manifold.

The purpose of this study is to determine the level of tank stratification that can be maintained in a direct solar system using conventional flow rates and a flexible, fabric manifold. Stratification is characterized by vertical temperature profiles and a new mixing number based on the height weighted energy in the tank. Performance of the flexible manifold is compared to that of a conventional drop-tube inlet.

2. EXPERIMENTAL FACILITY

The experimental facility includes an insulated, plastic 372 liter water storage tank (UA = 2.7 W/K), a 310 liter electric water heater used to simulate collector return water, and a cold mains water supply. Tank temperatures are measured with 19 T-type thermocouples mounted in a thermocouple tree. Inlet water temperatures are measured with a thermocouple inserted in the pipe just upstream of the inlet. A turbine flow meter is used to measure the volumetric flow rate of the water entering the storage tank.

The conventional inlet is a vertical 2.54cm diameter PVC tube which delivers water to the top of the tank. The flexible manifold, shown in Fig. 1, is composed of a knit orlon sleeve clamped to a modified inlet tube. The fabric is also attached to a weight which rests on the bottom of the storage tank so that the manifold does not float to the top of the tank as air bubbles attach to the fabric. The vertical momentum of the incoming fluid is reduced by forcing the water from holes drilled around the circumference of a plugged drop tube. Flow from the tank into the manifold is not possible because the manifold collapses until the difference between the tank and manifold pressures is ≤0. Once the manifold fluid reaches the tank depth at which its density equals the tank fluid density, the fabric expands allowing flow from the manifold to the tank.

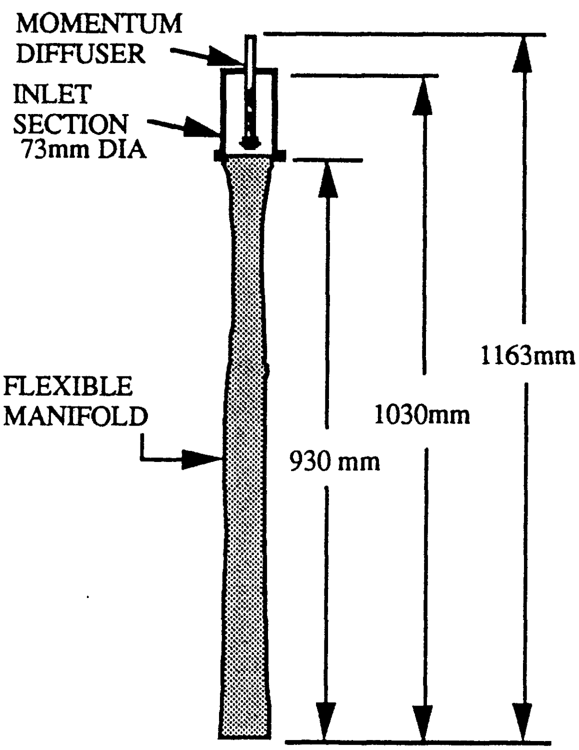


Fig. 1. Flexible manifold design

3. TESTING PROCEDURE

Three testing schemes are used to evaluate the two inlet designs. In each test, as water enters the storage tank from the inlet at the top of the tank, water is drained from the bottom of the tank at the same fixed flow rate (0.07 l/s based on conventional flow rates of 0.01-0.02 kg/s per m^2 of collector area). Tank temperature profiles, inlet water temperature, and flow rate are recorded at 1-minute intervals.

In Scheme I, the upper half of the tank is filled with hot (50-55°C) water and the bottom half is filled with cold (15-20°C) water. Water is then delivered to the tank at a constant intermediate temperature (30°C). The length of the test is 48 minutes which is sufficient time for the cold water to be removed from the tank (assuming no mixing occurs). In Schemes II and III, the storage tank is initially filled with 15-20°C water and test duration is 90 minutes, the time necessary to turn over the tank. In Scheme II, water is input at 50°C. In Scheme III, temperature of the inlet water is varied every 10 minutes as shown in Table 1.

TABLE 1 SCHEME III INLET TEMPERATURES

Time (minutes)	T_{inlet} (°C)
0 - 10	50
10 -20	40
20 - 30	30
30 - 40	30
40 - 50	40
50 - 60	50
60 - 70	40
70 - 80	30
80 - 90	40

4. RESULTS

In a preliminary study of 13 synthetic fabrics, a 7.3 cm diameter, orlon manifold was determined to be the most effective at achieving and maintaining stratification (6). In general, materials which perform most effectively are loosely-knit synthetic fabrics which stretch easily in one direction and maintain physical integrity even after long exposure to high temperature water (7,8). Stratification levels in the storage tank equipped with this best flexible manifold are compared to stratification levels in the same tank equipped with a conventional drop-tube.

4.1 Temperature Profiles

Normalized tank temperature profiles obtained at 8-minute intervals during Scheme I tests are plotted in Figs. 2(a) and (b), for the conventional inlet and flexible manifold, respectively. The ordinate is the normalized tank height, the distance from the bottom of the tank (Y) divided by the total tank height (H). The abscissa is the normalized tank temperature defined as the local temperature (T) minus the initial minimum tank temperature (T_c) divided by the maximum initial tank temperature difference (T_h-T_c). The thick solid line (final-str) represents the theoretical temperature profile that would exist at the end of the test if no mixing occurred. This ideal case is numerically predicted using a plug flow model with no mixing. The simulated tank is initially made up of isothermal disks of volume and temperature consistent with the experimental conditions. Losses to the surroundings are taken into account. The thinner solid line (final-mix) is determined theoretically by assuming that any time water enters the tank, the entire tank mixes completely. The mass weighted average temperature of the experimental tank at the beginning of a test is used as the initial condition for the mixed tank model.

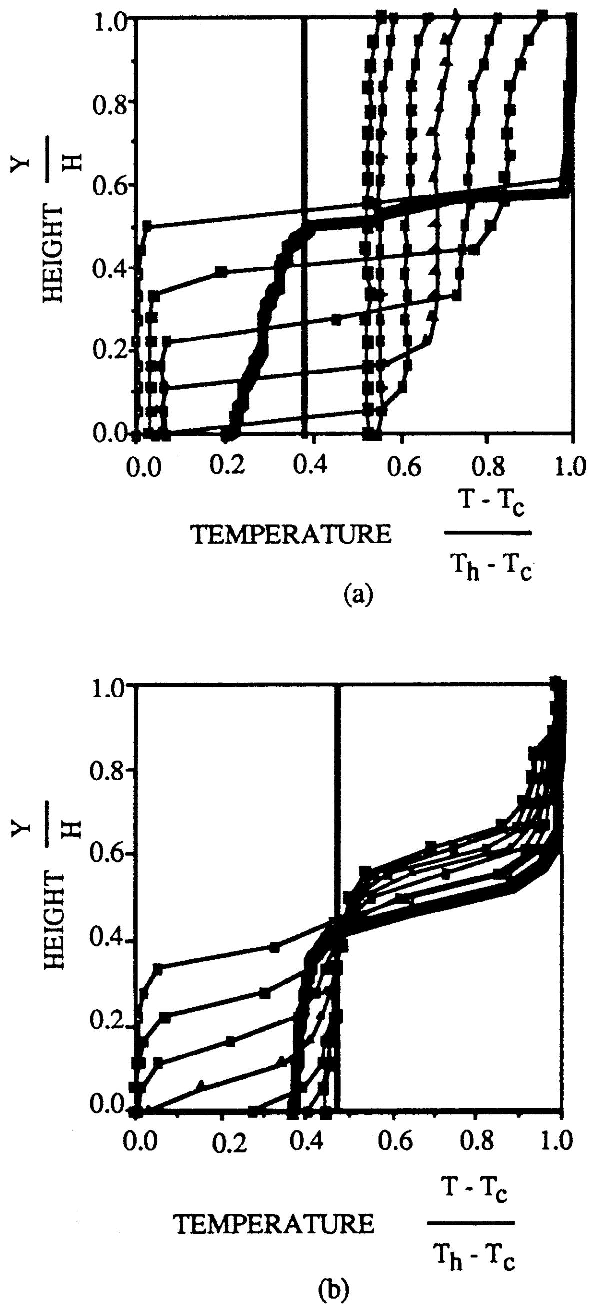


Fig. 2. Scheme I tank temperature profiles
(a) conventional inlet (b) flexible manifold
(-0 min., -8 min., -16 min., -24 min., -32 min., -40 min., -final(exp), -final(str), -final(mix)).

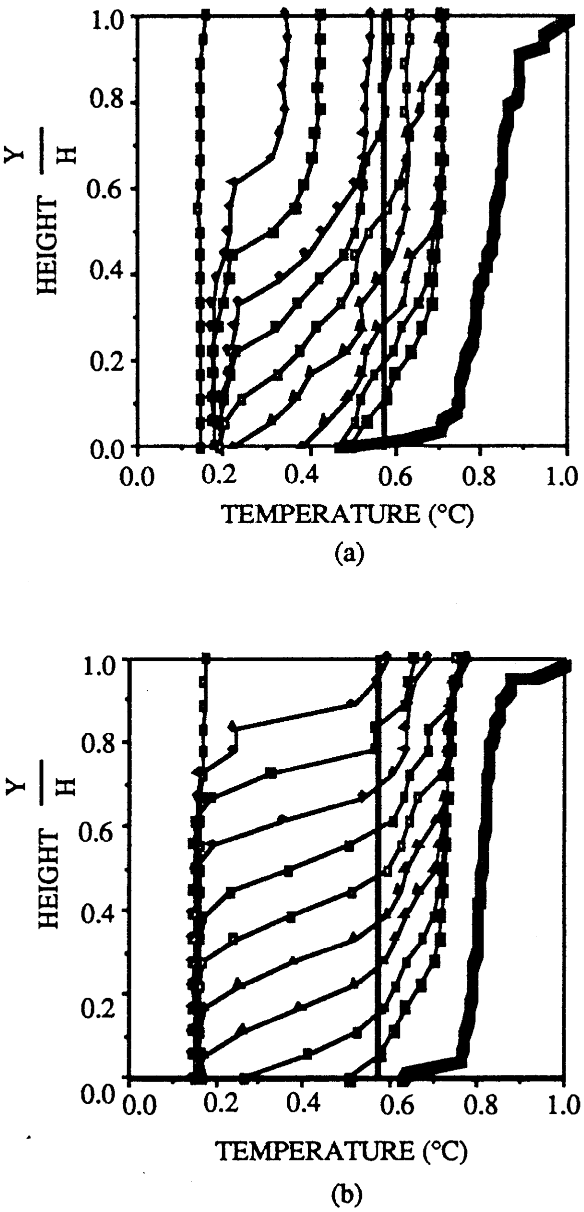


Fig. 3. Scheme II tank temperature profiles (a) conventional inlet (b) flexible manifold.
(-0 min., -10 min., -20 min., -30 min., -40 min., -50 min., -60 min., -70 min., -80 min., -final(exp), -final(str), -final(mix)).

As shown in Fig. 2(a), in the ideally stratified tank, water in the upper half of the tank remains at the initial temperature (minus losses to the surroundings), and water in the lower half of the tank is at the temperature of the incoming fluid. In both the simulated fully-mixed tank and the conventional tank, the tank is isothermal at the end of the test; however, since in the actual tank, mixing occurs only in the top half of the tank, total energy stored in the conventional tank is greater than that predicted for a fully-mixed tank. This result points out the fallacy of basing level of mixing on only the slope of the temperature profile. As shown in Fig. 2(b), use of the flexible manifold significantly reduces mixing. At the end of the test, water temperatures in the upper half of the tank are only slightly lower than those predicted by the stratified tank model and in the lower half of the tank, measured water temperatures are only slightly greater than in an ideal tank.

Tank temperature profiles for Scheme II tests are plotted in Fig. 3. Temperature is plotted at 10-minute intervals as a function of normalized vertical position. In both these tests and Scheme III tests, temperatures are not normalized since there are not constant hot and cold bounding tank temperatures. Inspection of the tank temperature profile after the first 10 minutes reveals that the temperature at the bottom of the tank is increased when using the conventional inlet. This temperature rise indicates that some mixing occurs throughout the entire tank. During this same time, the flexible manifold restricts mixing to the top third of the tank.

Tank temperature profiles obtained under Scheme III are plotted in Fig. 4. As in Scheme II, mixing occurs throughout the conventional tank after only 10 minutes and at the end of the 90 minute test, the tank is nearly isothermal. In contrast, as shown in Fig. 4(b), use of the flexible manifold restricts mixing and in the lower portion of the tank, the final temperature profile is nearly identical to that predicted for a stratified tank. In the upper part of the tank, measured temperatures are as much as 10°C less than in the ideal case, but are significantly higher than in the conventional tank.

4.2 Mix Number

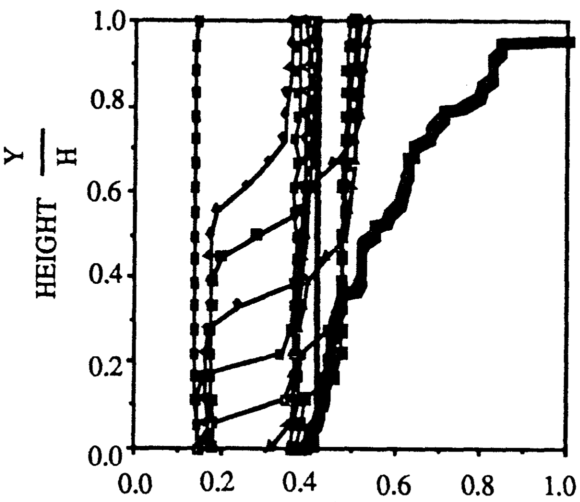
A new quantitative measure of tank stratification is based on the energy in the storage tank weighted by vertical location. The mix number is,

$$\mathrm{MIX\#} = \frac{(M_{str} - M_{exp})}{(M_{str} - M_{mix})}, \tag{1}$$

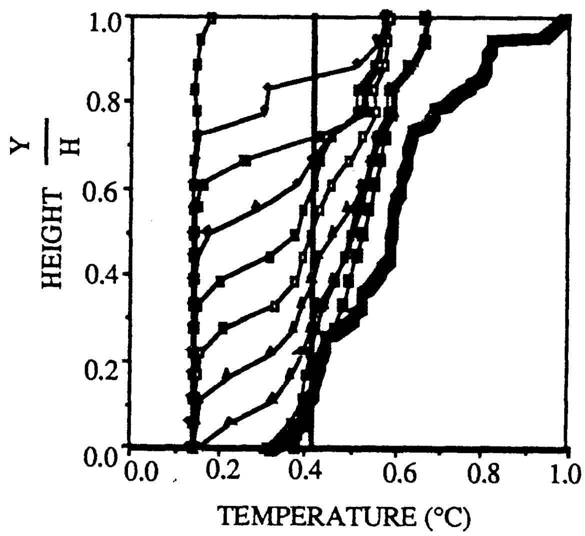
where M is the first moment of energy given by,

$$M = \int_0^H y\,dE = \sum_{i=1}^{n} y_i E_i, \tag{2}$$

for a tank of height H, with n isothermal nodes. The distance measured from the bottom of the tank to the center of node i is y_i, and $E_i = \rho_i c_{p_i} V_i T_i$. The mix number has a value of zero for a tank with a measured moment of energy (M_{exp}) equal to that predicted by the fully stratified tank model (M_{str}). Mix number equals one if the experimental moment of energy equals the moment of energy predicted by the fully mixed tank model (M_{mix}).



(a)



(b)

Fig. 4. Scheme III tank temperature profiles
(a) conventional inlet (b) flexible manifold
(-0 min., -10 min., -20 min.,
-30 min., -40 min., -50 min.,
-60 min., -70 min., -80 min.,
-final(exp), -final(str), -final(mix)).

Mix numbers for the conventional drop-tube inlet and the flexible manifold are compared in Table 2. As expected from tank temperature profiles, the mix number associated with the flexible manifold is much less (closer to the perfectly stratified value of zero) than the mix number calculated for the tank using the conventional drop-tube.

The use of the flexible manifold improves stratification under each of the three testing schemes compared to the conventional drop tube inlet. Under Scheme III, with the realistic conditions of variable inlet temperature associated with variable insolation for constant flow rate systems, the flexible manifold reduces mixing by 48 percent compared to the conventional inlet.

TABLE 2 MIX NUMBER

Inlet Type	Scheme I	Scheme II	Scheme III
Conventional Drop-Tube	.620	.556	.737
Flexible Manifold	.161	.401	.383

5. SUMMARY

A new mix number based on height weighted energy gives an accurate indication of thermal stratification in solar storage tanks. Mix numbers obtained in a 372-liter tank indicate that a knit orlon flexible manifold is 48 percent more effective than a conventional drop-tube at achieving tank stratification.

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